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and Reflectance Spectra of a Dilute
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and Space Administration

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SUMMARY

NASA is participating with other federal agencies in the surveillance of ocean dumping activities and the monitoring of oceanic conditions and the effects of dumping. Part of this work involves laboratory measurements of upwelled spectral signatures of various concentrations of industrial waste products mixed with water in a large water tank. This paper describes two such experiments. The laboratory arrangement, some test equipment, and results of two experiments are presented. Radiance and reflectance spectra are presented for a biosolid waste product mixed with conditioned tap water and natural river water. Results of these experiments indicate that reflectance increases with increasing concentration of the sludge at practically all wavelengths for concentrations of total suspended solids up to 117 ppm in conditioned tap water and 171 ppm in natural river water. Significant variations in the spectra were observed and may be useful in defining spectral characteristics for this waste product. No significant spectral differences were apparent in the reflectance spectra of the two experiments in the two types of base water, especially for wavelengths greater than 540 nm. Reflectance values, however, were generally greater in natural river water for wavelengths greater than 540 nm. Reflectance may be considered to increase linearly with concentration of total suspended solids from 5 to 171 ppm at all wavelengths without introducing errors larger than 10 percent.

INTRODUCTION

The National Aeronautics and Space Administration is participating with other federal agencies in the surveillance of ocean dumping activities and monitoring of oceanic conditions and the effects of dumping (refs. 1 to 4). The immediate objective of NASA in this effort is to evaluate the feasibility of using remote sensing systems such as multispectral scanners on aircraft to monitor the movement and dispersion of these dumped materials. As remote sensing systems improve and spectral signatures of waste materials are understood more clearly, it may become possible to define and map the concentration levels of these materials without concurrent sea truth data. Development of this technology could possibly lead to a satellite remote sensing system to locate, identify, map, and quantify pollution features in the coastal zones and oceans.

Large quantities of solid waste materials are dumped into the oceans each year. Recently, for example, over 7 million metric tons (8 million tons) of municipal and industrial waste products and 22 million m³ (30 million yd³) of contaminated dredge spoil were disposed of in this manner in 1 year (ref. 1). Evidence indicates that these waste materials in large, concentrated amounts could change the natural oceanic environment, adversely affect ecological systems, and create a potential hazard to human health. To minimize the probability of these undesirable effects occurring specific areas in the oceans have been designated by the Environmental Protection Agency (EPA) for disposing of

these waste materials (ref. 5). In addition, a comprehensive and continuing program of monitoring and research regarding the effects of the dumping of waste materials into ocean waters (ref. 5) is conducted by the National Oceanic and Atmospheric Administration (NOAA) with NASA participation.

In 1975, 11 ocean disposal sites were in active use. Three of these were located in the Gulf of Mexico (ref. 5). One of these, the Western Gulf Site, was used by the Shell Chemical Company of Deer Park, Texas, under EPA special permit number 730D008F, to dispose of an industrial biosolid waste product (sludge) from February 1976 to August 1977. In July 1977 a dump was made at this site from a moving barge (line dump) while remotely sensed multispectral scanner data were collected by a NASA aircraft (ref. 6). Samples of the sludge material were shipped to Langley Research Center (LaRC) for spectral signature experiments using a large water tank. The results of these experiments are the subject of this paper.

The objectives of these experiments were to measure the radiance and reflectance spectra of the biosolid sludge at various concentrations in two types of base water; to determine the linearity or nonlinearity of the reflectance with concentration; and to provide data to aid in the interpretation and understanding of the flight-test data. To accomplish these objectives the sludge was mixed with two base water types in steps to obtain several mixture concentrations. Radiance spectra were measured for the base waters and each mixture concentration. Reflectance spectra were calculated from these data and are presented as a function of wavelength and mixture concentration. Results of the experiments are discussed and a brief description of the laboratory as well as some of the components in the laboratory arrangement is given. These experiments were conducted in August and September 1977 on two samples of biosolid waste.

SYMBOLS

A	area of spectrometer entrance slit, cm^2
D	vertical displacement of oscilloscope measurement, cm
$E(\lambda)$	spectral irradiance, $\text{W}/\text{m}^2\text{-nm}$
K	ratio of instrument throughput to vertical-scale sensitivity factor, $\frac{\text{cm}^2\text{-sr}}{\text{mW}/\text{nm}\text{-cm}}$
$L_u(\lambda)$	upwelled spectral radiance, $\frac{\text{mW}/\text{nm}}{\text{cm}^2\text{-sr}}$
P(λ)	spectral power, mW/nm
S	vertical-scale sensitivity factor, $\text{mW}/\text{cm}\text{-nm}$

λ	wavelength, nm
$\rho_u(\lambda)$	spectral reflectance, percent of input (relative to a 100-percent diffuse reflector)
Ω	acceptance solid angle of spectrometer, sr

LABORATORY AND EQUIPMENT

Figure 1 is a sketch of the laboratory arrangement. Major parts of the setup include a water tank, circulation system, filtration and deionization system, solar simulator, first-surface mirror, and rapid-scan spectrometer. A black canvas tent covers the water tank to block out background radiation during testing and to minimize the amount of contaminants, such as dust, entering the water tank. A brief description of the laboratory and equipment follows. Further descriptive material is found in reference 7.

The water tank has a volume of about 12.5 m^3 . The interior is coated with a black phenolic paint that absorbs 97 percent of incident radiation. After the tank is filled with water, the circulation system is used to maintain a homogeneous mixture in the tank. This is accomplished by pumping water from two drains in the bottom of the tank through a system of pipes which returns the water to the tank through four vertical pipes along the interior walls of the tank. Tests using tracer techniques and transmission measurements have confirmed that this circulation system maintains a uniform mixture throughout the tank for particle sizes less than $100 \mu\text{m}$. The deionization and filtration system removes suspended materials, organic materials, and dissolved ionic substances. Generally after tap water is conditioned through this system, it contains less than 0.5 ppm of suspended solids and less than 2 ppm of dissolved substances.

The simulated solar radiation spectrum is produced by a 2.5-kW xenon short-arc lamp. A collimated light beam is projected onto the surface of the water by a mirror positioned above the water tank. (See fig. 1.) The angle of incidence of the beam with the surface of the water is 13° . The simulated spectrum is similar to a sea-level standard solar radiation curve (Solar elevation = 30°) often used in engineering calculations (fig. 2, from ref. 8). The intensity of the light at the surface of the water is approximately 8 percent of the sea-level standard.

The rapid-scanning spectrometer system consists of a spectrometer unit with a telephoto lens attachment and a plug-in unit with an oscilloscope and camera attachment. The spectrometer unit with telephoto lens attachment is mounted 2.43 m above the surface of the water. (See fig. 1.) The spectrometer uses a Czerny-Turner grating monochromator without an exit slit. The spectral output of the monochromator is focused on the target of a vidicon tube, where the spectrum is stored as an electrical charge image. An electron beam periodically scans the vidicon target to convert the charge image into an electronic signal. This signal is processed by the plug-in unit, which functions as an electronic signal processor and controller between the spectrometer

and the oscilloscope. The signal is displayed on the oscilloscope and is photographically recorded with the camera.

The spectrometer is designed to measure power per spectral bandwidth (spectral power). The oscilloscope screen is used to show displacement of the instrument measurement. Oscilloscope displacement is proportional to spectral power, as shown in the following equation:

$$D = \frac{P(\lambda)}{S} \quad (1)$$

The signal is internally processed in such a manner that the vertical-scale sensitivity factor S has a constant value over the wavelength range from 400 to 980 nm. Values of S were obtained by the manufacturer using calibration procedures described in reference 9. (After receipt of the instrument, the manufacturer's calibration was checked in an approximate manner prior to the tests described herein.)

The upwelled spectral radiance $L_u(\lambda)$ is defined as

$$L_u(\lambda) = \frac{P(\lambda)}{A\Omega} \quad (2)$$

where A is the area of the spectrometer entrance slit and Ω is the acceptance solid angle of the spectrometer. Radiance values given in this document are based on power received at the detector and are not corrected for losses through the telephoto lens. Tests with and without the lens indicate that such losses are much less than 5 percent for wavelengths between 400 and 980 nm.

Combining equations (1) and (2) results in

$$L_u(\lambda) = \frac{DS}{A\Omega} \quad (3)$$

or

$$L_u(\lambda) = \frac{D}{K} \quad (4)$$

where

$$K = \frac{A\Omega}{S}$$

Thus, upwelled spectral radiance is determined from displacement and the proportionality constant K , which is a function of the calibration factor S (which includes optical transmissivity) as well as acceptance angle Ω and slit area A .

The spectral resolution of the spectrometer for these experiments was 32 nm. The accuracy of the radiant power measurements based on the manufacturer's spectrometer specifications is ± 20 percent between wavelengths of 400 and 600 nm and ± 12 percent between 600 and 967 nm. Included in the error is a repeatability uncertainty of ± 13 percent between 400 and 600 nm and ± 3.5 percent between 600 and 967 nm. Discussions with a representative of the manufacturer of the instrument indicate that these values represent 3 σ error bands. Also, there is a wavelength error on the order of ± 10 nm for each radiant power measurement because of temperature variations, repeatability, and digital readout errors. Because of these errors, spectral radiances from tests conducted on different days usually differ somewhat in magnitude. The overall shape of the spectra over the wavelength range is quite consistent between tests conducted on different days, however.

EXPERIMENTAL METHOD

Radiance spectra measurements were made for several concentrations of the sludge in two types of base water. Tap water conditioned by the filtration and deionization system was used as one of the base water types and water from Back River¹ without conditioning was pumped into the tank for the other. Table I shows a comparison of the two base water types. Samples of the sludge were collected from storage facilities of the Shell Chemical Company at Deer Park, Texas. These samples were transported on ice in coolers to LaRC and kept under refrigeration until the experiments were conducted. Table II shows typical physical and chemical characteristics of the sludge. Numbers in the first column were taken from the EPA special ocean dumping permit 730D008F issued to Shell Chemical Company and represent typical values for the biosolid waste. Numbers in column 2 represent results of an analysis on samples of the sludge that was barged to the site and dumped in July 1977. Samples of this material were brought to LaRC and used in the Back River water experiment in August 1977. A separate batch was obtained later from the Shell storage facility and tested in conditioned tap water in September 1977. Values in columns 3 and 4 for these two batches were measured in the laboratories at LaRC. Before each experiment all of the remaining sludge was put into a drum and mixed for several hours

¹Back River is located in Hampton, Va., on the western side of Chesapeake Bay and about 16 km from its mouth.

with a small trolling motor. A sample of the mixture was taken and analyzed for total suspended solids. These values (column 3) were used to estimate the volume of sludge required for addition to the water tank (11 600 liters) to achieve a desired concentration of total suspended solids in parts per million. These estimated values of total suspended solids are indicated in figures 3(a) and 3(b). After each batch of sludge was added to the tank to achieve a desired concentration and the spectral signature was measured, a sample was taken from the water tank. These samples were taken by lowering a sample bottle below the surface and allowing the bottle to fill. These samples were later analyzed for total suspended solids. Measured values are indicated in parentheses in figures 3(a) and 3(b). Differences in the estimated and measured values, especially for the higher concentrations, may be due to formation of precipitates.

In preparation for an experiment, the water tank was filled to within 0.3 m of the top with 11 600 liters of water. The sludge was mixed with conditioned tap water to obtain concentrations of total suspended solids of 7, 18, 28, 39, 62, 85, and 117 ppm and with water from Back River to obtain total concentrations of 60, 80, 115, 135, and 171 ppm. Before sludge was added, the conditioned water had approximately 2.0 ppm suspended solids and Back River water had 56 ppm which included about 20 ppb of chlorophyll a. The concentrations of total suspended solids were selected, particularly those in conditioned tap water, to cover the range believed to exist in plumes several minutes after an ocean dumping operation occurs.

After the tank was filled, the circulation system was activated and the water was allowed to circulate until a steady-state condition existed in the tank. During this period and again after the experiment, radiance spectra of a neutral test white card (100 percent reflectance) were measured with the test card placed near the surface of the water. These data were used to normalize the sludge radiance spectra so that spectral differences would be more easily recognized.

Following the test-card measurements, an upwelled radiance spectrum for the base water was obtained. Then the proper amount of sludge was mixed with the water to achieve the desired concentration of suspended solids. This mixture was again allowed to circulate for approximately 15 minutes until the sludge was evenly distributed throughout the tank, and an upwelled spectrum was measured as before. (See ref. 7.) Additional sludge was added to achieve the next desired concentration of suspended solids. This procedure was repeated to obtain upwelled spectra for the other concentrations. Generally, after the water tank was filled, 2.5 to 3.0 hours were required to complete an experiment.

RESULTS AND DISCUSSION

Measured spectral radiance curves are shown in figure 3. Figure 3(a) shows the radiance variations with wavelength and concentration for the sludge mixed with conditioned tap water. Figure 3(b) shows similar data for the sludge mixed with Back River water. The spectral radiance values at any particular concentration and wavelength are an average over the optical bandwidth. For example,

values shown at 600 nm are an average of values from 584 to 616 nm (for a spectral resolution of 32 nm). Concentrations of total suspended solids for each mixture are indicated on the curves. Major spectral variations in these data between 750 and 950 nm for each concentration are caused by the spectral characteristics of the input xenon light source. Data reduction procedures intro-

duce a random error estimated to be $\pm 2.2 \times 10^{-7}$ $\frac{\text{W/nm}}{\text{cm}^2\text{-sr}}$ and could possibly

account for small variations in these curves. At $\lambda = 580$ nm (fig. 3(a)) this error is about ± 10 percent of the radiance value for the conditioned water (2-ppm) curve and ± 2 percent for the 117-ppm curve. In figures 3(a) and 3(b) the radiance increases at all wavelengths with increasing concentration of suspended solids. Peak radiance values occur near $\lambda = 580$ nm, especially for the higher concentrations.

Selected data from figures 3(a) and 3(b) are shown in figure 3(c). These curves show the differences between the radiance spectra for the sludge in conditioned tap water and in Back River water. The shapes of these curves are essentially the same. For wavelengths less than 500 nm, radiance values are greater in conditioned tap water than in Back River water for the same total suspended solids. This difference may be due to absorption by chlorophyll or other material present in the Back River water.

Figure 4 shows input radiance spectra (white-card data) that were measured before and after each experiment. On the basis of the 3 σ instrument inaccuracies specified by the manufacturer, these data should not differ by more than 20 percent at wavelengths less than 600 nm and 12 percent at wavelengths greater than 600 nm. In figure 4 these differences are not exceeded for wavelengths less than 600 nm but are for most wavelengths greater than 600 nm. Experience with the instrument has shown that for experiments conducted on separate days, white-card measurements may differ but are within the error bands and are usually much smaller than differences obtained for these experiments. Specific sources of these discrepancies are unknown but could have been other systems in the laboratory arrangement.

Spectral reflectance curves for each concentration are shown in figure 5. Slight variations in either set of data in figure 3 or figure 4 may be amplified or attenuated because of the wavelength error and the effects will appear in figure 5. The decrease in reflectance in figures 5(a) and 5(b) between 400 and 440 nm is typical for clear oceanic waters, as may be seen in reference 10 (figs. 10 and 12, pp. 39 and 78), and is probably associated with the spectral characteristics of the base water. For concentrations less than 39 ppm in figure 5(a) reflectance is practically constant between 440 and 580 nm. For larger concentrations, reflectance increases with wavelength to a maximum value near 580 nm. The decrease from the peak value was gradual for wavelengths less than 700 nm, with a sharp decrease between 700 and 740 nm. These features and the trend between 440 and 580 nm for the higher concentrations could be significant in determining unique spectral characteristics for this material. Typically for this laboratory (see refs. 7 and 11, e.g.) reflectance increased in the near-infrared wavelengths for most concentrations. It is suspected that this trend is also related to the spectral characteristics of the base water.

A comparison of the reflectance data for both types of base water is shown in figure 5(c). Mixture concentrations for these curves are the same as those for the radiance data shown in figure 3(c). Spectral differences of the sludge in the two base water types are best illustrated in figure 6. These curves were obtained by normalizing each curve in figure 5(c) by the reflectance value at 580 nm, which is the peak value for most of the concentrations of total suspended solids.

Figure 7 shows reflectance as a function of concentration of total suspended solids for wavelengths between 400 and 900 nm. These data were selected from figures 5(a) (solid curve) and 5(b) (dashed curve). Reflectance was generally higher in Back River water than in tap water. These curves indicate a nonlinear variation of reflectance with concentration of total suspended solids, especially at the lower concentrations. The assumption of linearity for all wavelengths and for concentrations of total suspended solids greater than 5 ppm would not introduce errors larger than 10 percent. This information is important to researchers using remotely sensed data with limited ground support data.

CONCLUDING REMARKS

Radiance and reflectance spectra for a biosolid waste product were obtained in two types of base water for concentrations of total suspended solids in the sludge from 7 to 117 ppm and wavelengths from 380 to 970 nm. The following results were obtained from these laboratory measurements:

1. Reflectance increased with increasing concentration of the total suspended solids at practically all wavelengths. Peak values occurred near 580 nm for most of the spectra.
2. Significant variations in the reflectance spectra of each experiment were evident and may be useful in determining a spectral signature for this waste product.
3. Reflectance values were generally higher in river water for wavelengths greater than 540 nm for similar concentrations of total suspended solids. Spectral differences were greater for wavelengths less than 540 nm.
4. The reflectance may be considered to increase linearly with concentration of total suspended solids at all wavelengths and at concentrations from 5 to 171 ppm without introducing errors greater than 10 percent.

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January 9, 1979

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TABLE I.- CHARACTERISTICS OF BASE WATER TYPES

	Conditioned tap water	Back River water
Total suspended solids, ppm	1.9	56.0
Average volatile, ppm	1.6	19.0
Average nonvolatile, ppm	0.5	37.0
Chlorophyll <i>a</i> , ppb	0	23.0
Dissolved substances, ppm	<5	^a 15.0

^aThis number was not measured but is typical for this body of water.

TABLE II.- TYPICAL PHYSICAL AND CHEMICAL CHARACTERISTICS
OF THE BIOLOGICAL SLUDGE

	From dumping permit	Shell results	LaRC Aug.	Results Sept.
pH	6.0 to 8.0	-----	-----	-----
Specific gravity	1.01 to 1.05	-----	-----	-----
Total suspended solids, ppm . . .	30 000	14 700	16 300	17 250
Volatile suspended solids, ppm . .	23 000	12 000	12 700	14 720
Total organic carbon, ppm	12 000	5 580		
Liquid phase, carbon, ppm . . .	117	-----	-----	-----
Organic chlorides, ppm	0.800	-----	-----	-----
Mercury, ppm	0.011	-----	-----	-----
Solid phase, ppm		0.045		
Liquid phase, ppm		<0.001		
Cadmium, ppm	0.020			
Solid phase, ppm		0.003		
Liquid phase, ppm		0.002		
Arsenic, ppm	0.020			
Lead, ppm	0.050			
Copper, ppm	2.800			
Zinc, ppm	10.000			
Selenium, ppm	0.200			
Vanadium, ppm	0.200			
Beryllium, ppm	<0.004			
Chromium, ppm	40.000			
Nickel, ppm	2.500			

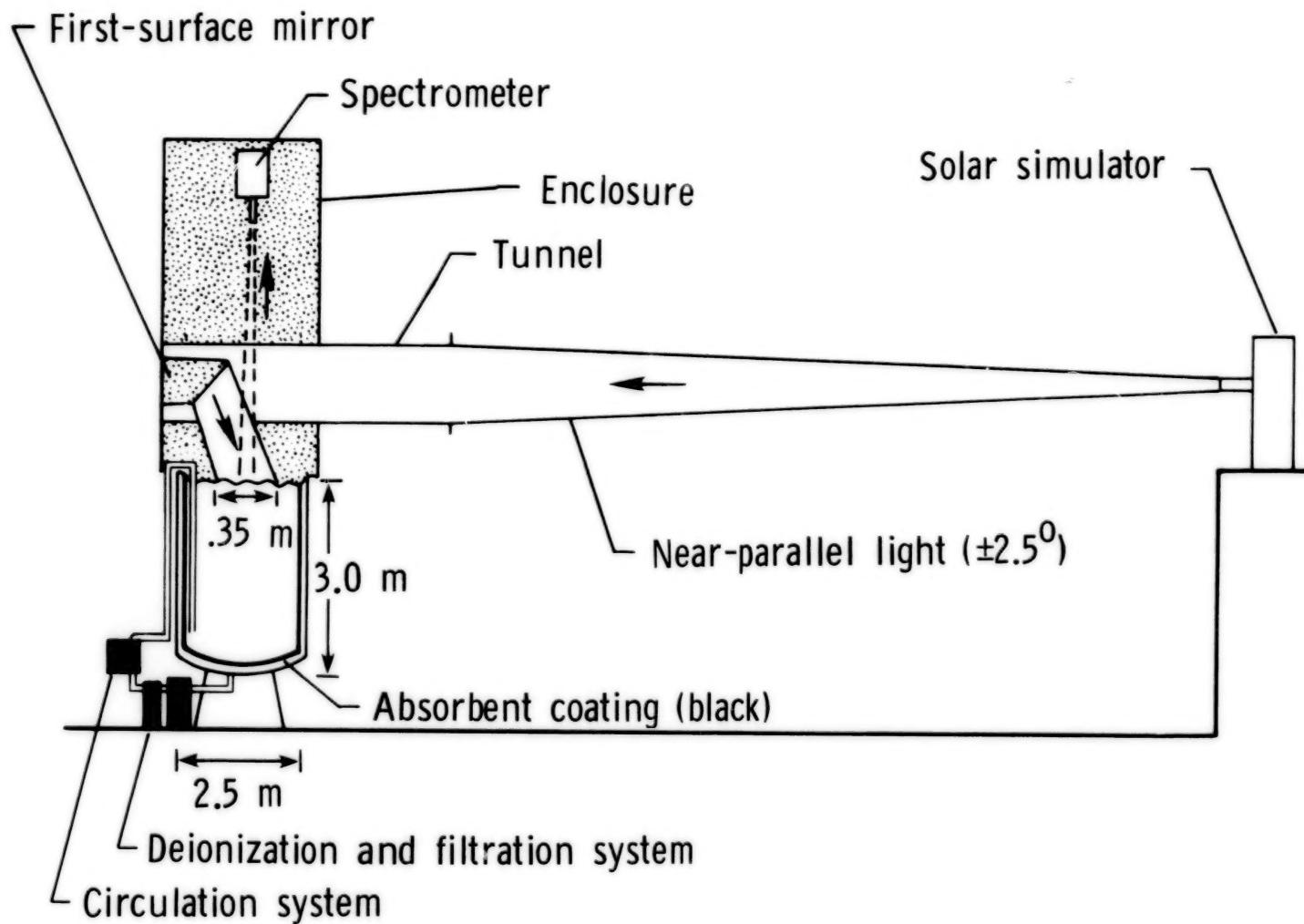
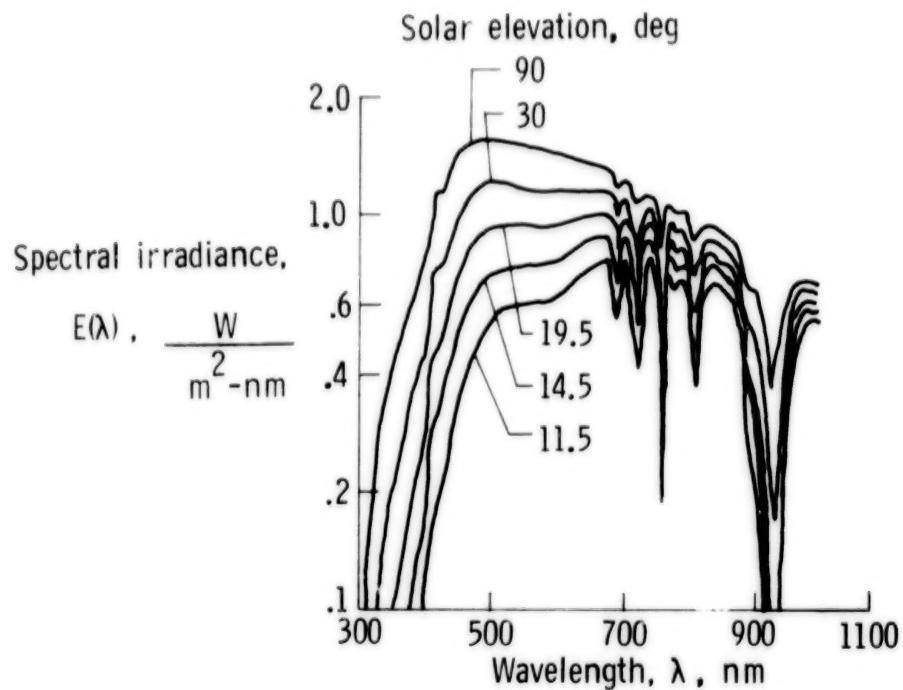
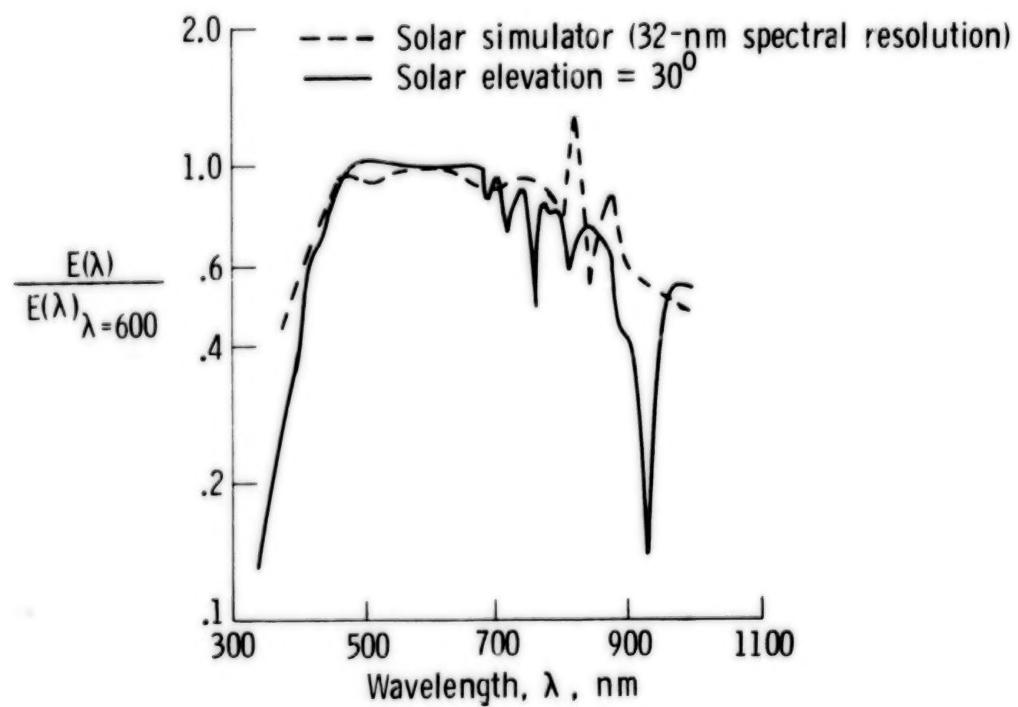


Figure 1.- Sketch of laboratory setup.

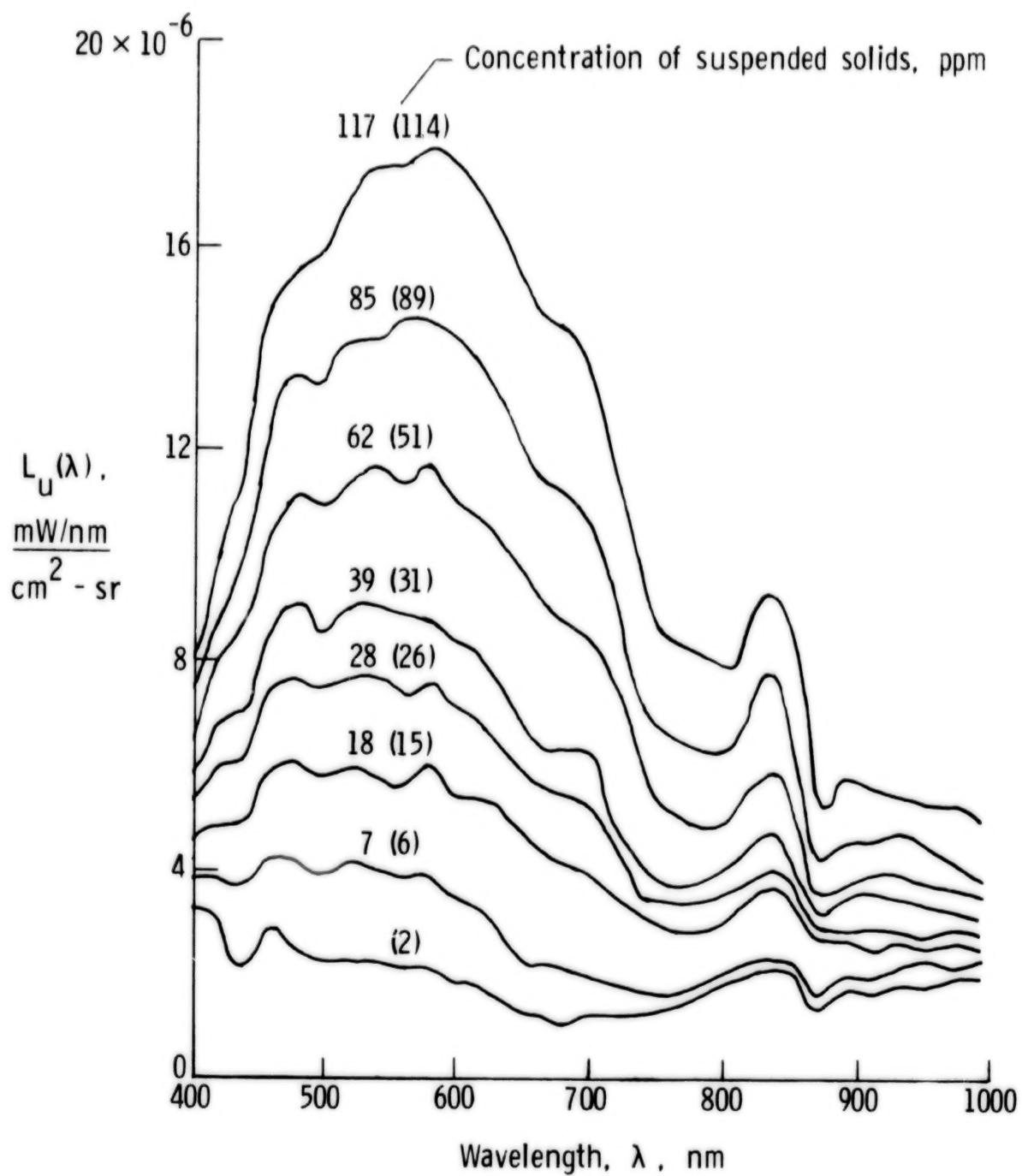


(a) Standard sea-level solar irradiance spectra (ref. 8).



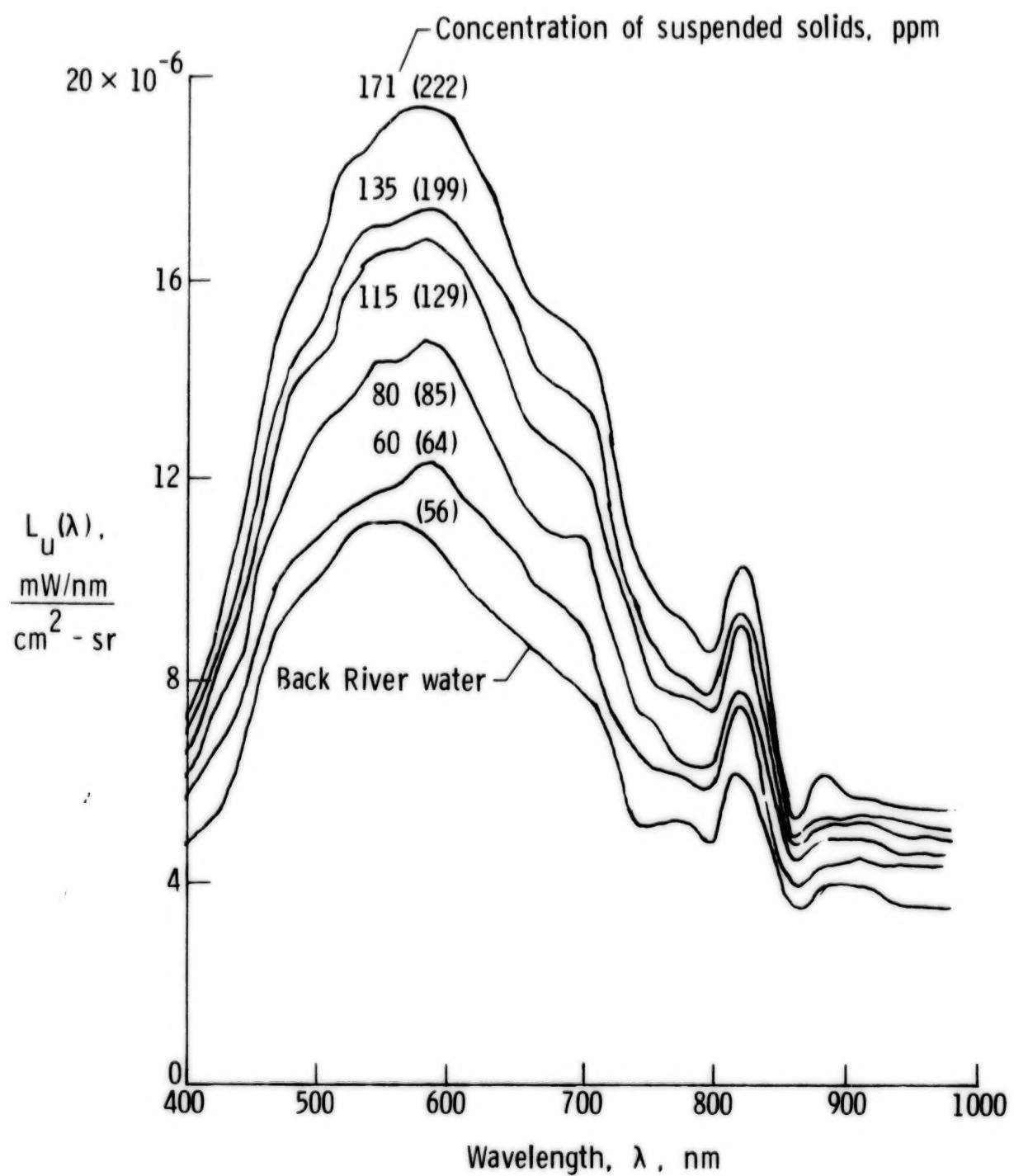
(b) Solar simulator and standard sea-level spectra.

Figure 2.- Standard sea-level solar irradiance spectra and comparison with solar simulator data.



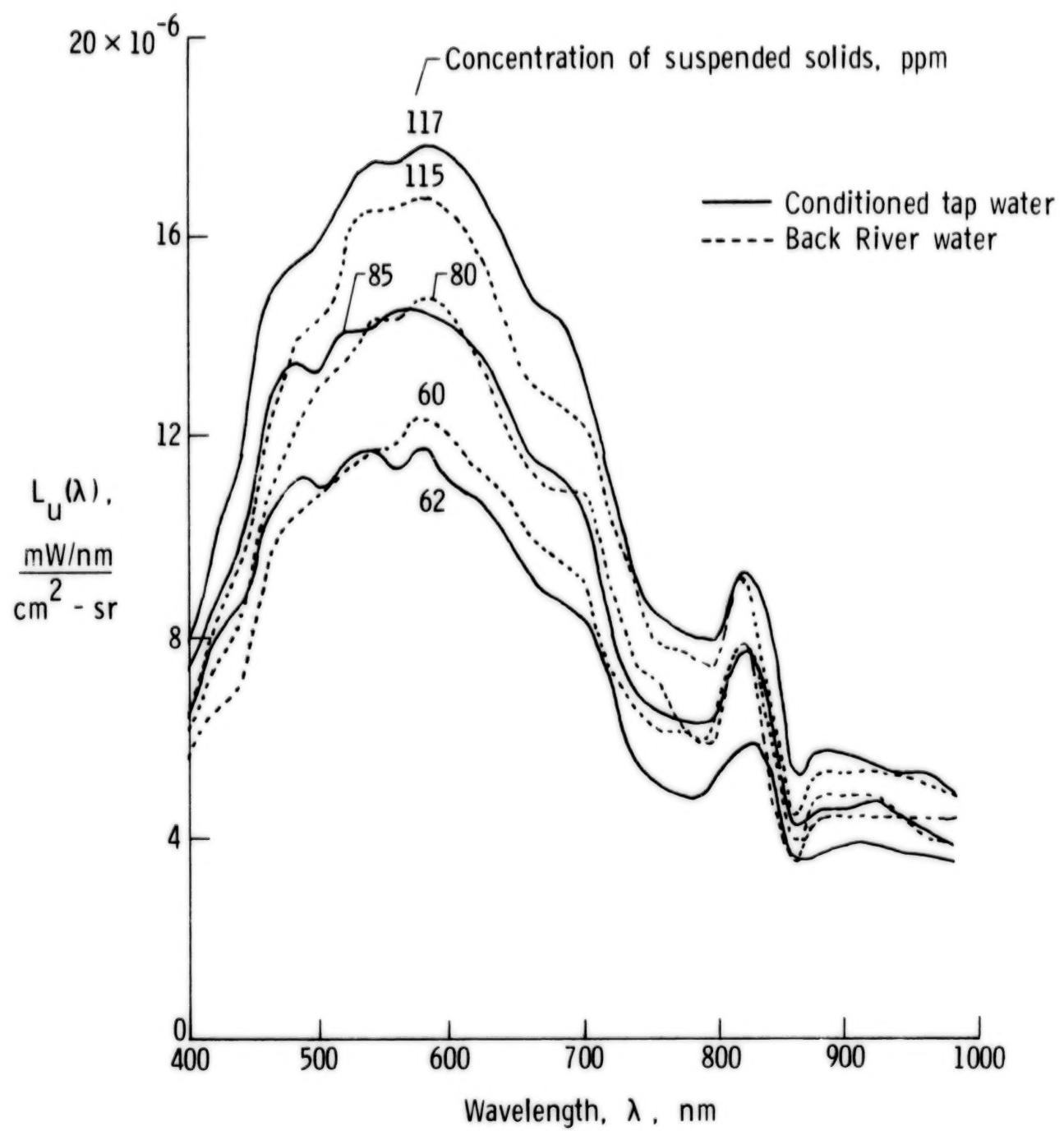
(a) Conditioned tap water as base water.

**Figure 3.- Upwelled radiance plotted against wavelength.
Spectral resolution, 32 nm.**



(b) Back River water as base water.

Figure 3.- Continued.



(c) Comparison of radiance data in the two base water types.

Figure 3.- Concluded.

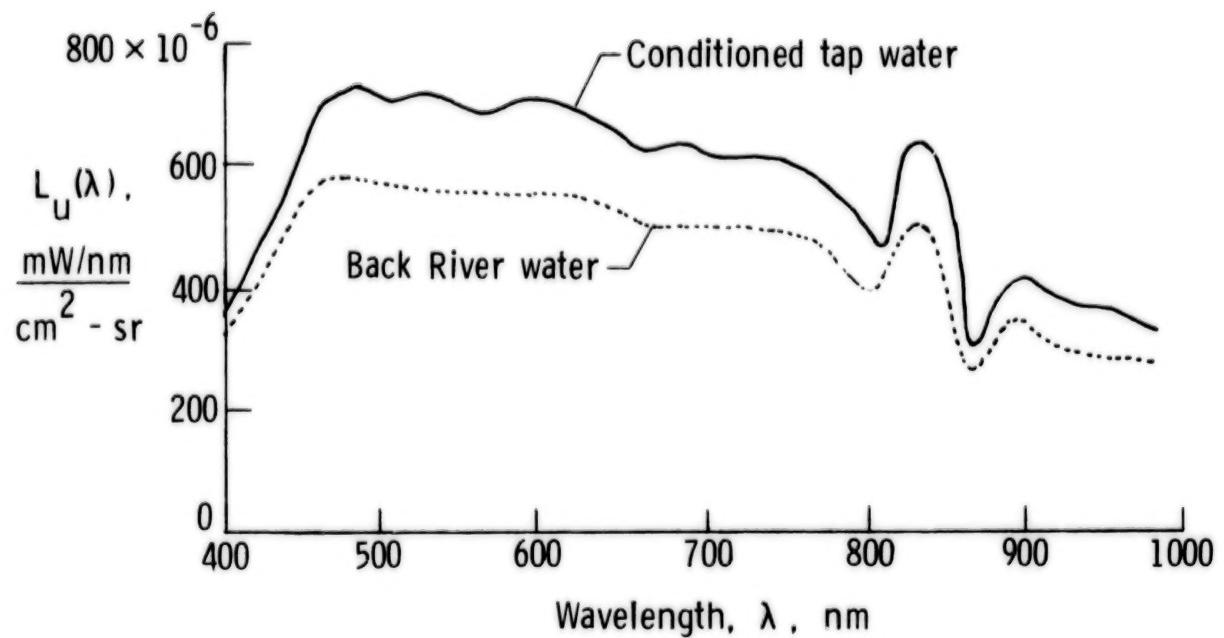
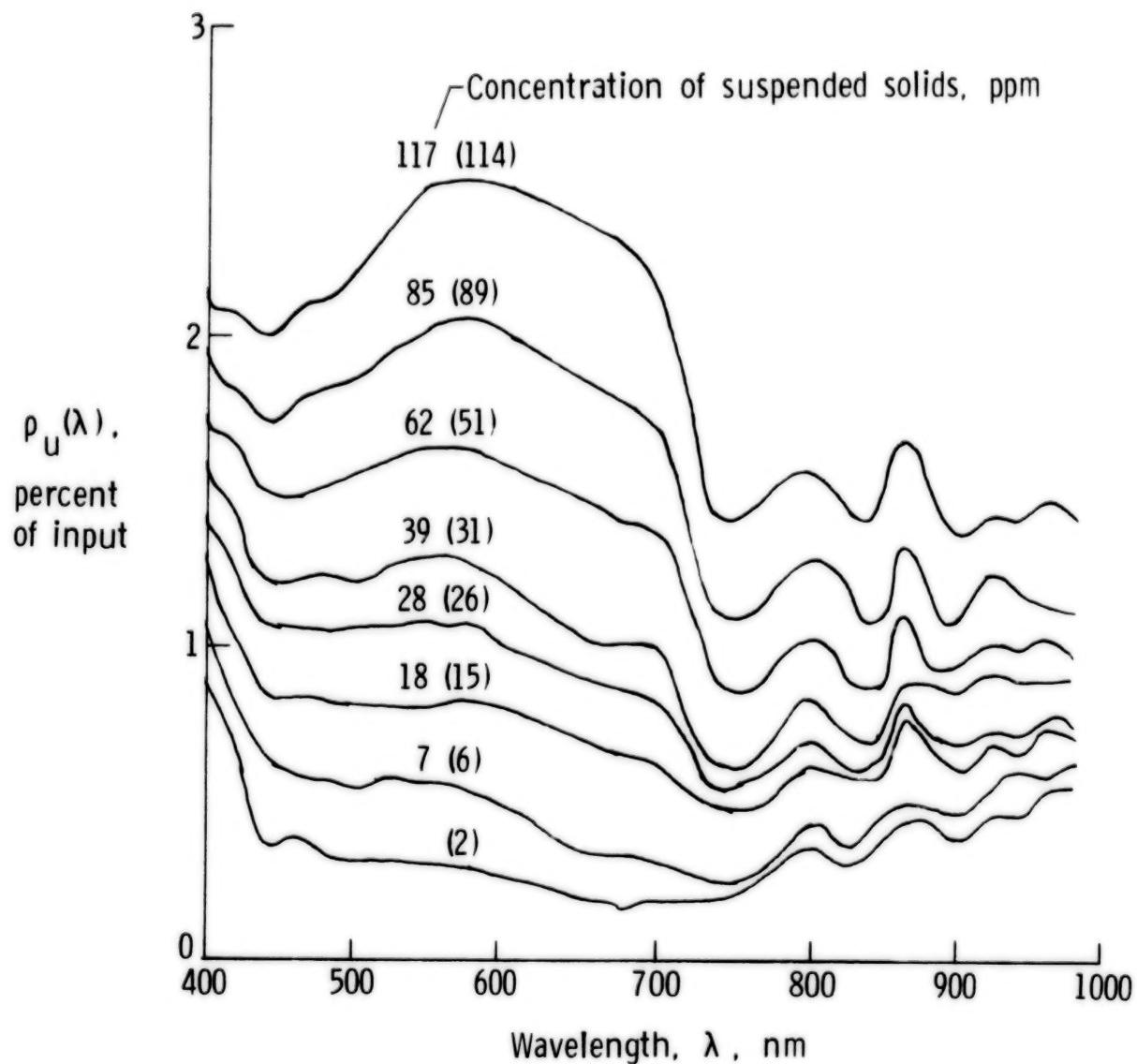
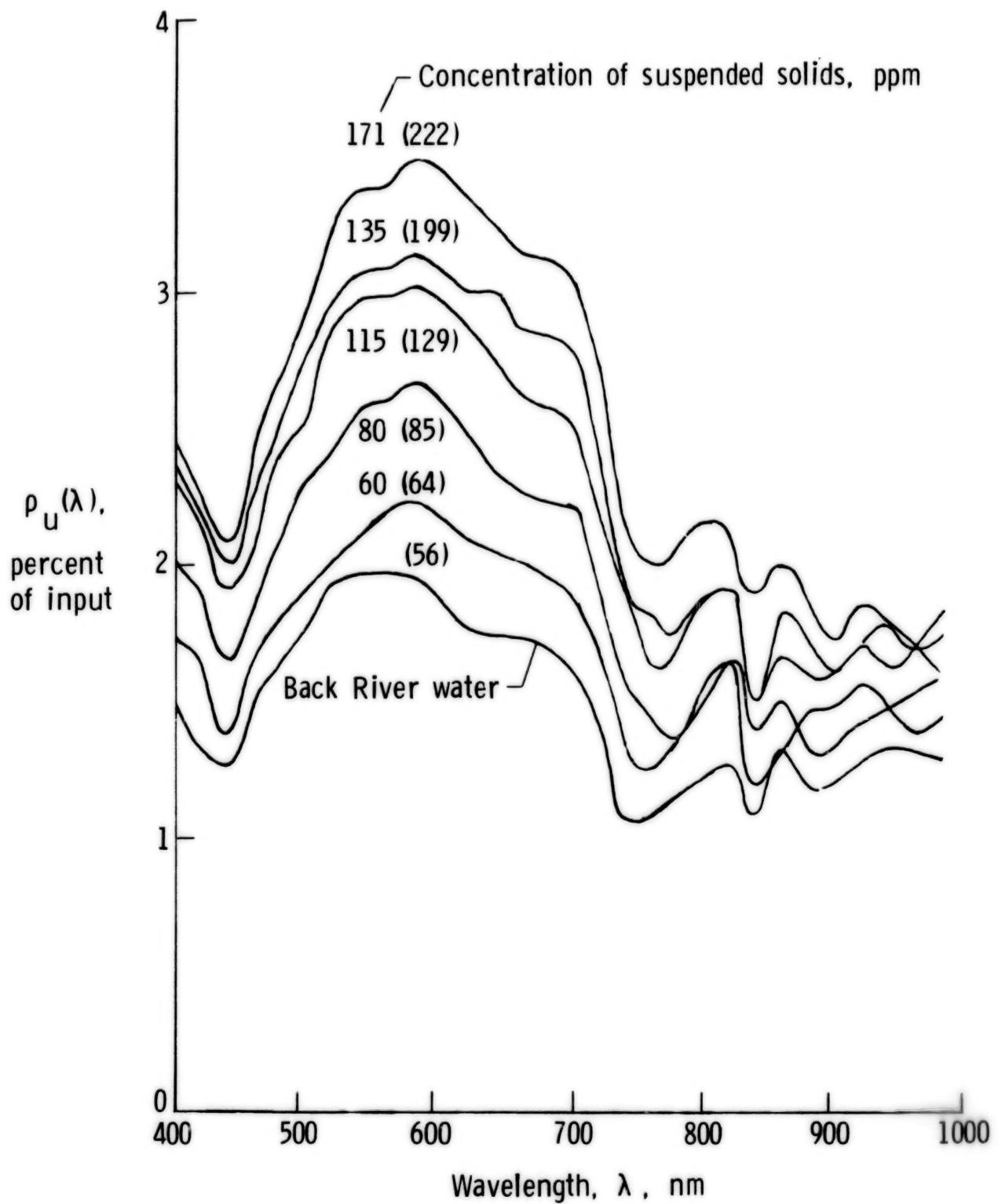


Figure 4.- White-card radiance data plotted against wavelength.
Spectral resolution, 32 nm.



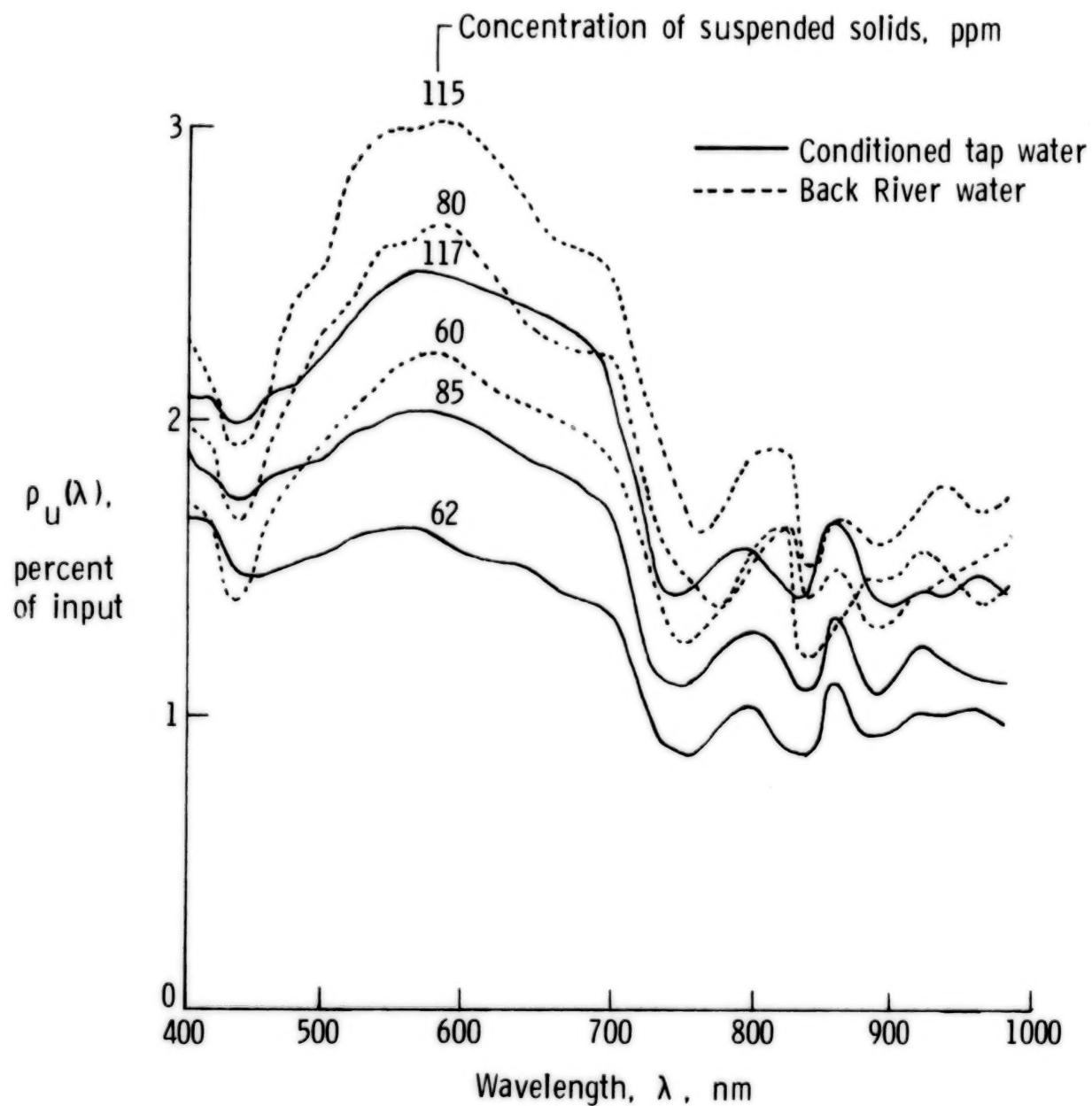
(a) Conditioned tap water as base water.

Figure 5.- Upwelled reflectance plotted against wavelength.
Spectral resolution, 32 nm.



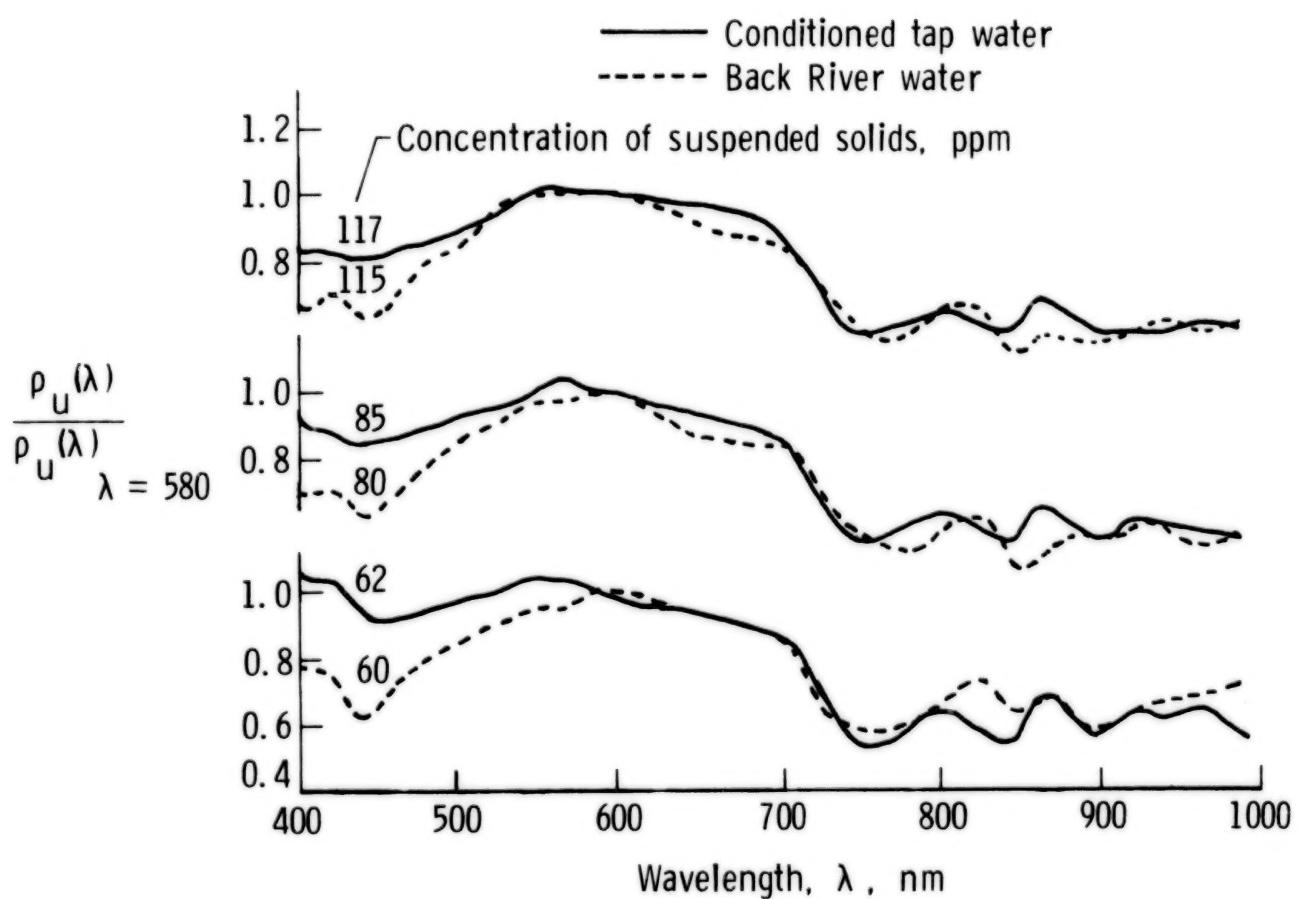
(b) Back River water as base water.

Figure 5.- Continued.



(c) Comparison of reflectance data for the two base water types.

Figure 5.- Concluded.



**Figure 6.- Comparison of normalized reflectance spectra
in the two base waters.**

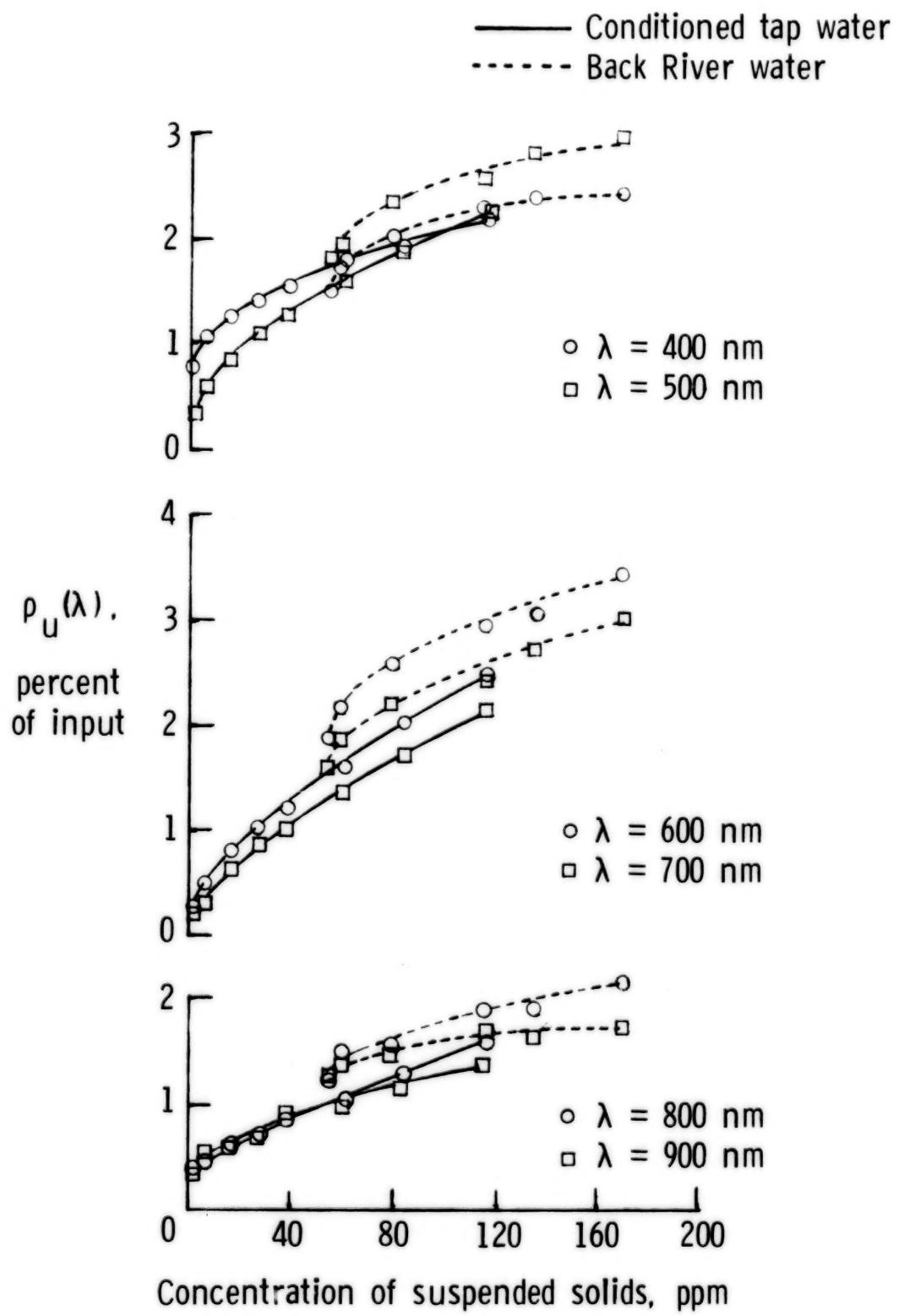


Figure 7.- Upwelled reflectance plotted against concentration of total suspended solids for the two experiments.

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